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THIN-FILM GUIDED-WAVE DEVICES FOR INTEGRATED/FIBER OPTIC
SIGNAL PROCESSING AND COMMUNICATIONS

Annual Scientific Report

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Prepared By

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Research efforts for this program year were focused on topics as listed in the Introduction. For topic #1, a theoretical analysis on the ultimate deflector limitations as determined by the various sources of phase distortions in the SAM has been completed. Experimental verification of the theoretical predictions is yet to be completed due to the lack of fabrication facility for GHz SAW transducers. Since topic #2 and topic #3 have been practically unexplored previously but were believed to possess great future potential, a considerable amount of effort was spent on necessary preparations for in-depth studies of these two topics. The preparations include preliminary theoretical formulation of the problems, establishment of laboratory facilities for fabrication of the devices, and construction/assembly of a large variety of required optical and RF equipments.		

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20. ABSTRACT (Continued)

Some very significant progress has been achieved in both topics. For example in Topic #2, the theoretical analysis has uncovered a very efficient wideband Bragg diffraction configuration which involves a single-mode optical waveguide in the (001) plane of a GaAs substrate with the SAW propagating in the <100> direction. A paper in connection with topic #2 was presented at the 1982 Ultrasonics Symposium and a proceeding paper was subsequently published.

In regard to topic #4, some effort was also spent in the study and realization of a Hybrid Integrated Acoustooptic Time-Integrating Correlator Module which utilizes anisotropic Bragg diffraction. Some preliminary results were published in the Technical Digest of 1982 Topical Meeting on Integrated Optics while more refined results were published in the Proceedings of 1982 Ultrasonics Symposium.

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I. INTRODUCTION

Integrated or Guided-Wave Optics is an emerging technology that has the ultimate potential of integrating miniature optical components such as laser light sources, modulators, switches, deflectors, lenses, prisms, and detectors in a common substrate. The resultant integrated optic circuits and subsystems are expected to have a number of advantages over the conventional bulk optical systems in certain areas of applications. Some of the advantages include smaller size and lighter weight, wider bandwidth, lesser electrical drive power requirement, greater signal accessibility, and integratability. The integrated optic circuits are also expected to possess advantages in stability, reliability, ruggedness, and ultimate cost. It has been recognized for some time that the most immediate applications of integrated optics lie in the areas of wideband multichannel communications and signal processing (for both civilian applications such as fiber optic systems and military hardwares such as sensors and radars).

The general objectives of this research program are to study the basic physical mechanisms/phenomenon of new and novel guided-wave devices with application to wideband multichannel optical information processing.⁽¹⁾ The major tasks that have been carried out during this program year include theoretical and experimental research on the following four specific topics:

1. Wideband Acoustooptic Bragg Cell Using A Tilted-Finger Chirp Transducer,
2. Guided-Wave Acoustooptic Interactions and Devices in ZnO/GaAs Waveguides,
3. Guided-Wave Magneto-Optic Bragg Diffraction and Devices in YIG/GGG Waveguides, and
4. Hybrid Integrated Acoustooptic Time-Integrating Correlator Using Anisotropic Bragg Diffraction.

Some significant progress has been made in each research topic.

II. PROGRESS DURING CURRENT PROGRAM YEAR

A. Summary of Research Achievements

Research efforts for the current program year have been focused on topics as listed in the Introduction. For topic #1, a theoretical analysis on the ultimate deflector limitations as determined by the various sources of phase distortions in the SAM has been completed. Experimental verification of the theoretical predictions is yet to be completed due to the lack of fabrication facility for GHz SAW transducers. Since topic #2 and topic #3 have been practically unexplored previously but were believed to possess great future potential, a considerable amount of effort was spent on necessary preparations for in-depth studies of these two topics. The preparations include preliminary theoretical formulation of the problems, establishment of laboratory facilities for fabrication of the devices, and construction/assemblage of a large variety of required optical and RF equipments. Some very significant progress has been achieved in both topics. For example in Topic #2, the theoretical analysis has uncovered a very efficient wideband Bragg diffraction configuration which involves a single-mode optical waveguide in the (001) plane of a GaAs substrate with the SAW propagating in the $\langle 100 \rangle$ direction. A paper in connection with topic #2 was presented at the 1982 Ultrasonics Symposium and a proceeding paper was subsequently published.

In regard to topic #4, some effort was also spent in the study and realization of a Hybrid Integrated Acoustooptic Time-Integrating Correlator which utilizes anisotropic Bragg diffraction. This particular project was not listed in the original proposal but was jointly supported by the AFOSR and the NSF during the past year. Some preliminary results were published in the Technical Digest of 1982 Topical Meeting on Integrated Optics while more refined results were published in the Proceedings of 1982 Ultrasonics Symposium.

Finally, continued efforts were also made to complete establishment of the microfabrication facility for integrated optical and SAW devices.

B. Research Progress

A more detailed description of the progress and the achievements now follows:

1. Wideband AO Bragg Cell Using A Tilted-Finger Chirp Transducer

The tasks of this research project are to carry out theoretical and experimental studies aimed at determining the ultimate limitations of the Wideband

AO Bragg Cell Using a Tilted-Finger Chirp Transducer (Fig. 1) which had evolved from an earlier AFOSR program.^(2,3) Specifically, phase front distortions of the SAW which result from the varying width and orientation of the finger electrodes across the transducer aperture and their impacts on the performance characteristics of the resultant Bragg Cell are to be studied. Three sources for phase distortions have been identified:

1. For each SAW frequency, different portions (segments) of the finger electrodes are effective. Since there exists a varying step height between each adjacent segments, an unwanted steering of the acoustic phase front is created. In some situations, the steering angle is so large that Bragg condition is totally destroyed. This effect can be detrimental unless some means is found to compensate it.
2. Similarly, for each SAW frequency, the propagation directions of the SAW from each effective segment of the finger electrodes diverge from each other. As a result, the diffraction efficiency, the Bragg bandwidth, and the beam profile of the deflected spots are all affected.
3. Both electric and mass loadings of the finger electrodes may cause distortions of the phase front of the SAW generated. A theoretical analysis which involves complex expressions and computer calculations has been carried out. This analysis shows that the wavefront distortions may cause detrimental effects on the diffraction efficiency and the AO Bragg bandwidth, especially as the center frequency and the bandwidth of the chirp transducer are increased. Unavailability of high-performance SAW transducers at 1GHz center frequency and above has kept us from experimental study aimed at verifying some of the predicted results. This experimental task will be pursued when such SAW transducers can be fabricated in the author's laboratory.

2. Wideband AO Interactions And Devices In ZnO/CaAs Waveguides

As indicated previously, integrated optic modules or circuits are expected to have a number of advantages over the conventional bulk counterparts in certain areas of optical signal processing applications. In fact, one example of such applications being very actively pursued by government agencies and industrial communities worldwide is real-time spectral analysis of very wideband radar signals.⁽³⁾ Another example which is expected to be picked up by the industrial communities is the acoustooptic time-integrating correlation under investigation at this author's laboratory.⁽⁴⁾ In both applications, wideband LiNbO_3 acoustooptic Bragg cells are used as the inter-

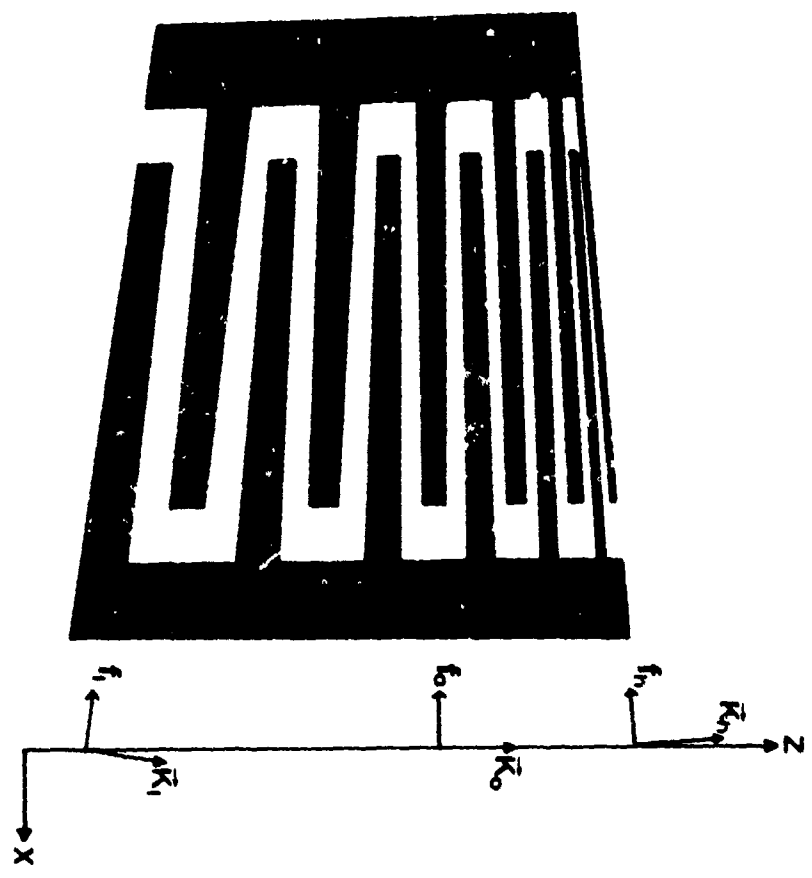


Fig. 1 A Tilted-Finger Chirp Transducer Evolved from A Large Number of Tilted Transducers of Staggered Center Frequency

face device between the light wave and the RF signals to be processed. In the meantime, utilization of integrated optics technology to other civilian applications such as fiber optic sensing, optical sensing in robotics technology, and optical computation have begun to receive genuine interest.

Despite the various successes of the LiNbO_3 -based wideband guided-wave AO Bragg devices referred to above, the ultimate advantages of integrated optics cannot be fully accomplished because it is difficult to realize a total or monolithic integration in a common LiNbO_3 substrate. This is due to the fact that LiNbO_3 is an insulating material and thus impossible to incorporate the diode laser or the photodetector array (both requiring semiconducting materials) in the same substrate. Consequently, only a partial or hybrid integration has been realized using the LiNbO_3 substrate. Clearly, an alternate substrate material is needed to realize monolithic integration. GaAs is a semiconducting material which has recently become a substrate material (only second to silicon in importance) for conventional integrated electronics. Meanwhile, as a result of recent advancement on the fabrication of the diode lasers and the photodetectors in GaAs waveguides, GaAs and related compounds are also at present considered the most promising candidate materials for monolithic integration of micro-optic components. Clearly, in comparison to the LiNbO_3 substrate, the GaAs substrate provides a greater future potential for integration of active and passive components that are required in information processing and communications applications. One of the key components in such future GaAs integrated optic circuits is an efficient wideband acoustooptic (AO) modulator/deflector. Some related study was reported previously by others.⁽⁵⁾ The AFOSR-supported research project is aimed at developing this key component.

In the theoretical study, we have discovered an interaction configuration of great interest, namely the one with the SAW propagating along the $\langle 100 \rangle$ or $\langle 110 \rangle$ direction of the (001) plane of a GaAs substrate.⁽⁶⁾ The analysis has shown that for SAW propagation directions such as those referred to above numerical computations can be simplified considerably to generate a variety

of design data unavailable heretofore. For example, it is shown that very efficient wideband Bragg diffraction is achievable by using the $\langle 100 \rangle$ - propagating SAW and a single-mode optical waveguide (See Fig. 2).

In the experimental study, we were convinced at the outset that establishment of an in-house RF sputtering facility for ZnO transducer would greatly expedite this research. Consequently, a great deal of effort was made toward the construction of a modern sputtering system at the author's laboratory. This construction has been completed (See Fig. 3). In fact, the system has gone through test run and has already produced good-quality ZnO SAW transducers on glass substrates. Although at lower degree of success some ZnO films were also deposited on $\text{Al}_x\text{Ga}_{1-x}\text{As}$ substrates for transduction of SAW at 200 MHz.

As a second step to the experimental study, the device configuration as shown in Fig. 4 was fabricated. A 2-micron thick piezoelectric ZnO film was first deposited on the GaAs waveguide by RF-magnetron sputtering system referred to above. A 200 MHz ID electrode (20 finger pairs and 1 mm aperture) was subsequently formed on the ZnO film. The very high refractive index of GaAs, namely, 3.4 at 1.15 micron wavelength has made excitation of GOW through prism coupling extremely difficult. Consequently, the (110) cleaved plane of GaAs was used to edge-couple the light beam. This preliminary AO Bragg cell has demonstrated high diffraction efficiency, namely, 50% diffraction at 47 mw RF drive power.⁽⁶⁾ This preliminary result is in line with the theoretical prediction. Improvements in waveguide and SAW transducer fabrication should produce even better results and closer agreement with the theoretical results.

3. Planar Guided-Wave Magneto-Optic Bragg Diffraction And Devices

As indicated in the original proposal,⁽¹⁾ this project concerns Bragg Interaction between Guided-Optical Waves and Magnetostatic Surface Waves in Thin-Film YIG/GGG Composite and its Application to Optical Information Processing. Since this research had been totally unexplored and since the experimental set-up for observation of Bragg diffraction phenomena predicted requires a large assortment of microwave and optical components a considerable amount of time and efforts have been spent in building and assembling of the experimental set-up from scratch. Although actual Bragg diffraction is yet to be demonstrated significant progress has been made toward this objective.

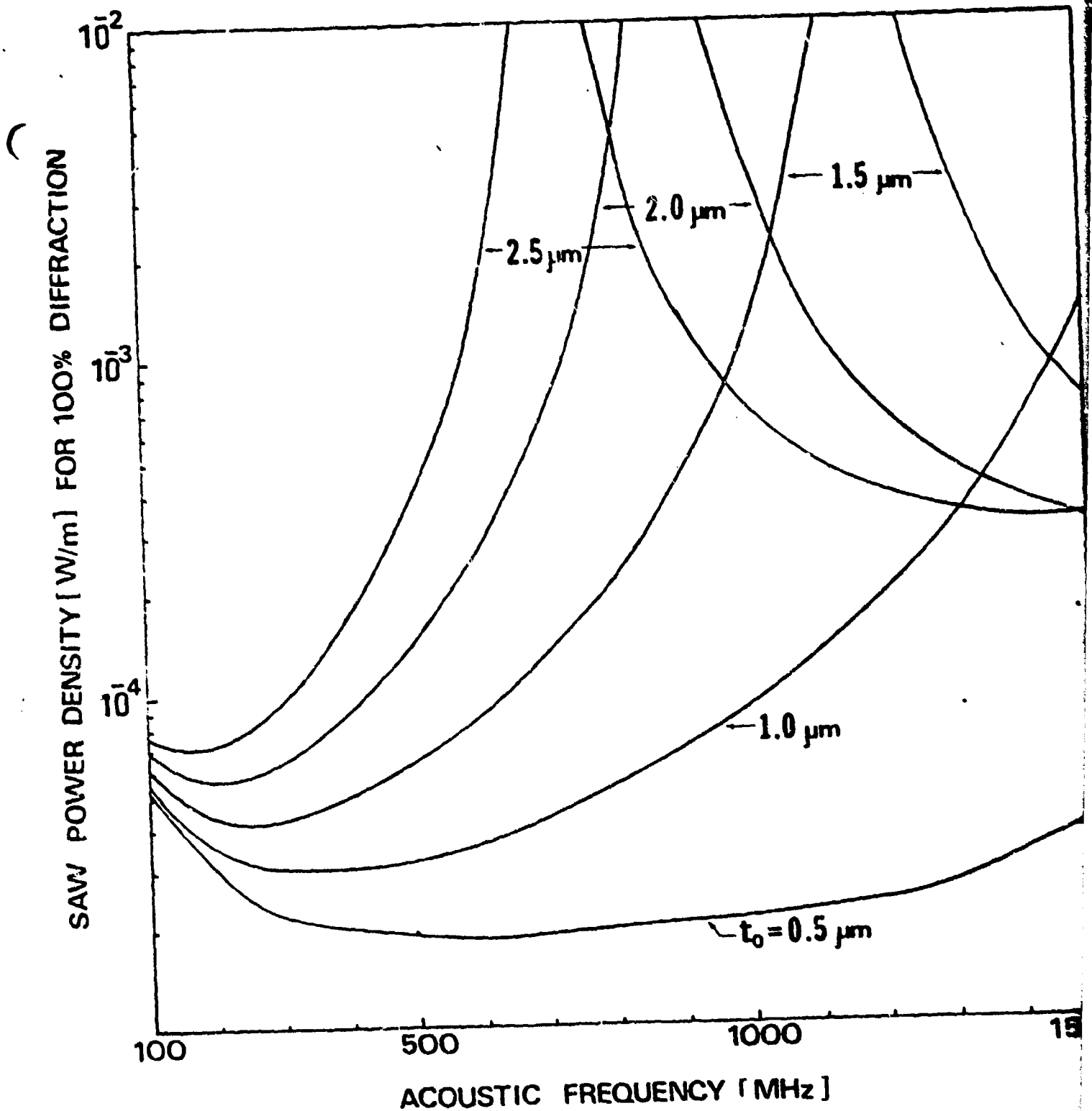


Fig. 2a SAW powerdensity v.s. Acoustic frequency for TE_0-TE_0 100% Bragg diffraction. SAW propagates along $\langle 110 \rangle$ on Z-cut GaAs waveguide whose thickness is represented by t_0 . The optical wavelength is $1.15 \mu\text{m}$.

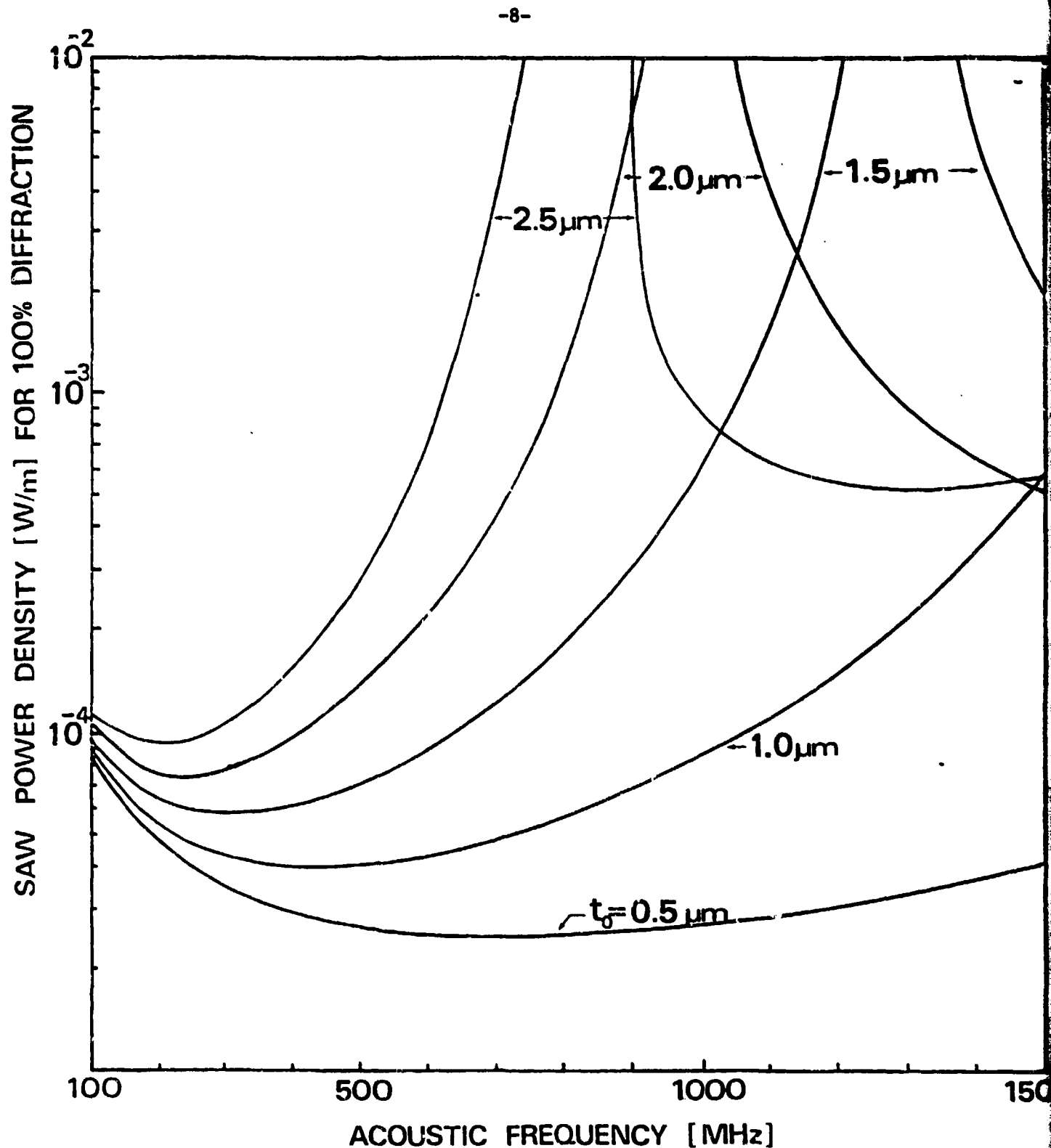


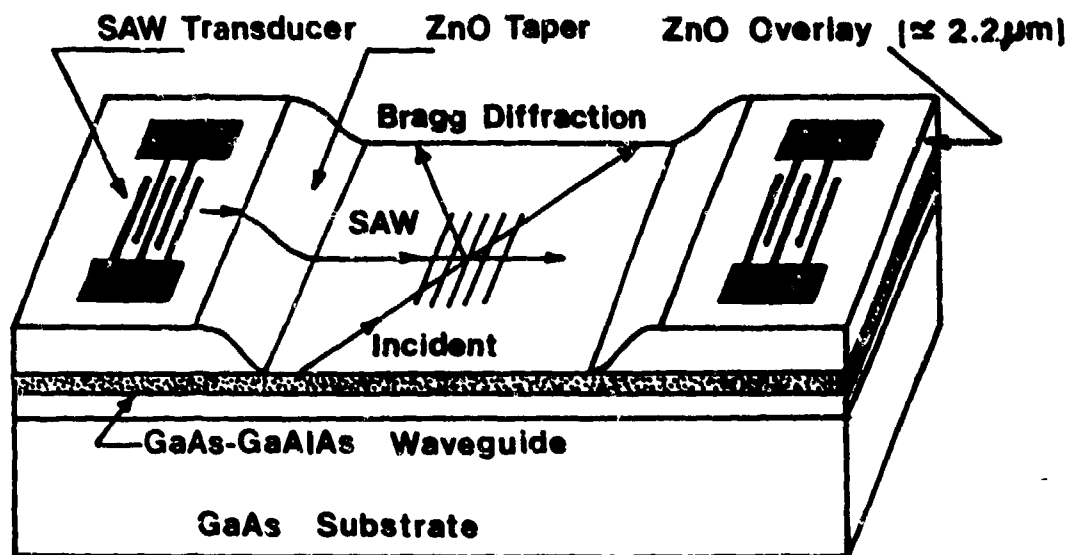
Fig. 2b SAW power density v.s. Acoustic frequency for $\text{TE}_0\text{-TE}_0$ 100% Bragg diffraction. SAW propagates along $\langle 100 \rangle$ on Z-cut GaAs waveguide whose thickness is represented by t_0 . The optical wavelength is a $1.15\mu\text{m}$.



FIGURE 3a RF SPUTTERING MACHINE



FIGURE 3b DIFFUSION AND
MECHANICAL PUMPS



**FIG. 4 Guided-Wave Acoustooptic Bragg Diffraction In
GaAs/GaAlAs-ZnO Composite Structure**

The experimental configuration being explored is shown in Fig. 5. The YIG/GGG sample furnished by Rockwell International was mounted on a specially-made holder and inserted in the air gap of an electromagnet. A microwave signal centered at 3.1 GHz was then applied to one of the metal strips to excite the magnetostatic surface waves (MSSW).⁽⁷⁻⁹⁾ The MSSW generated propagates in the plane of the sample and is detected by the other metal strip.⁽⁷⁻⁹⁾ By changing the magnitude of the D-C magnetic field the frequency of the MSSW has been tuned from 2.56 GHz to 3.55 GHz, demonstrating a bandwidth of 1 GHz. Fig. 6 shows a typical waveform of the MSSW that has been obtained using a pulse-modulated microwave carrier at 3.1 GHz. Note that the transit time between the two metal strips (at a separation of 0.96 cm) is approximately 160 ns. This time delay indicates a MSSW propagation velocity of 6.0×10^6 cm/sec which is about two orders of magnitude higher than that of the surface acoustic waves--potentially very desirable for high-speed optical information processing.

Following the successful excitation of the MSSW an attempt was undertaken to excite guided-optical wave using a He-Ne laser at 6328 Å as the second step toward actual magneto-optic Bragg diffraction experiment. Unfortunately, the optical insertion loss of the sample was found to be too excessive at this visible light wavelength to obtain any meaningful result. Subsequently, a Jodon He-Ne laser at 1.15 μm wavelength was ordered using the funds provided by the University. The laser arrived finally after a long delivery time but was found to be unoperational. This laser was shipped back to us recently after repairment. We have used the output of this laser and a pair of rutile prisms to excite and couple out guided-light beam. However, the very weak coupling observed thus far indicates that the thickness of the YIG film (~10 μm) is not optimum. New samples of various film thickness are being requested. In the meantime, a more sensitive photodetecting system at 1.15 μm is being constructed.

In summary, although actual Bragg diffraction from MSSW is yet to be demonstrated, significant progress has been made toward this objective.

4. Hybrid-Integrated Acoustooptic Time-Integrating Correlator Using Guided-Wave Anisotropic Bragg Diffraction

Time-integrating correlation of RF signals using bulk-wave isotropic AO Bragg diffraction has become a subject of great interest because of its applications in radar signal processing and communications.⁽¹⁰⁾ Some encourag-

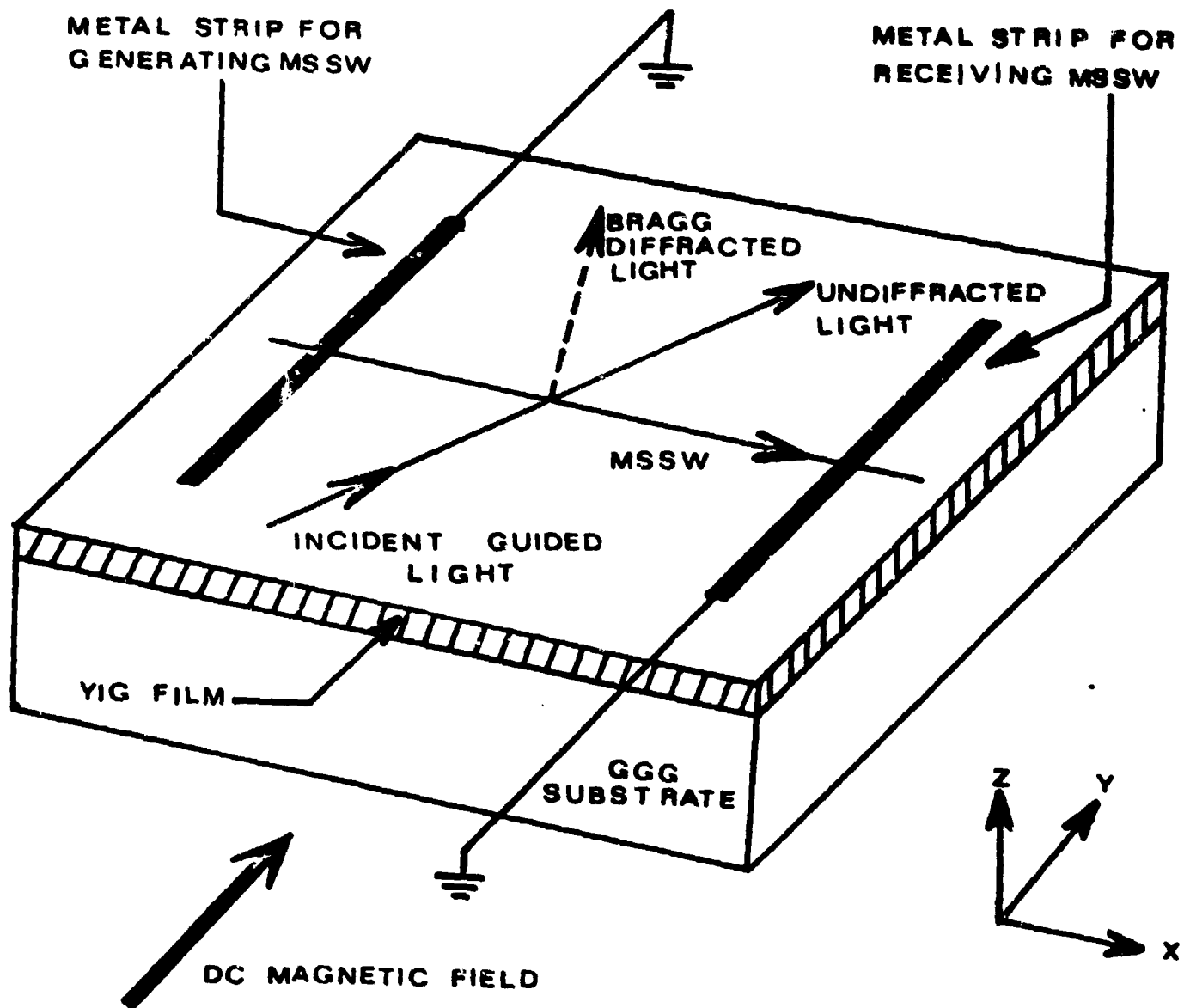


FIG 5 GEOMETRY FOR PLANAR GUIDED-WAVE MAGNETO-OPTIC BRAGG DIFFRACTION FROM MAGNETOSTATIC SURFACE WAVE

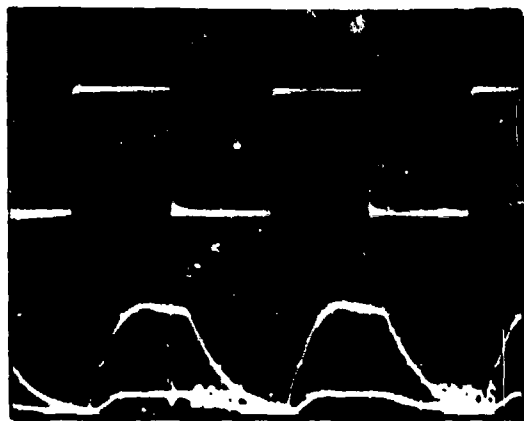


Fig. 6 Magnetostatic Surface Waves (MSSW)
at 3.1 GHz on YIG/CGG Layer Structure
Upper Trace: Waveform of Modulation
Pulse Bottom Trace: MSSW Pulse
Indicating A Time Delay of 160 ns
(Time Scale: 500 ns per major division)

ing results with the experiments that utilize guided-wave isotropic Bragg diffraction was reported earlier by us.⁽¹¹⁾ Subsequently, hybrid and monolithic structures for integrated optic implementations were suggested.^(12,3) In a conventional configuration that utilizes either bulk-wave or guide-wave isotropic Bragg diffraction, a pair of imaging lenses and a spatial filter are used to separate the diffracted light beam from the undiffracted light beam. Through the supports of the AFOSR and the NSF we have most recently explored a new and novel hybrid structure which utilizes guided-wave anisotropic Bragg diffraction and hybrid integration (see Fig. 7). This new structure can conveniently incorporate a thin-film polarizer to separate the diffracted light from the undiffracted light prior to detection and, therefore, eliminates the need of imaging lenses and spatial filter. As a result, the AO time-integrating correlator is not only much smaller along the optical propagation path and thus a much smaller optical insertion loss but also easier to be implemented in integrated optic format. A laser diode and a thin-film polarizer/photodetector array (CCPD) composite are butt-coupled to the input and the output end faces of a Y-cut LiNbO_3 plate (2mm x 12mm x 15.4mm), respectively. A single geodesic lens (with 8mm focal length is used to collimate the input light beam prior to interaction with the SAW. The SAW propagates at 5 degrees from the X-axis of the LiNbO_3 plate⁽¹³⁾ to facilitate anisotropic Bragg diffraction between TE_0 and TM_0 modes. In operation, the correlation between the two signals $S_1(t)$ and $S_2(t)$ is performed by separately modulating the laser diode and the RF carrier to the SAW transducer. Finally, the time-integrating correlation waveform is read out from the detector array by the charged-coupled device. Fig. 8(a) and 8(b) show, respectively, the autocorrelation waveforms of a 20 MHz modulation pulse signal (Pulse width = 0.05 μs) and a 12.5 MHz square-wave modulation signal (periodicity = 0.08 μs), both at the carrier frequency of 391 MHz.

In summary, encouraging results have been obtained in time-integrating correlation experiments which utilize guided-wave anisotropic Bragg diffraction in a Y-cut LiNbO_3 plate of very small dimensions (2mm x 12mm x 15.4mm).⁽¹⁴⁾ The preliminary experiment carried out with the correlator of incomplete hybrid integration at 0.6328 μm wavelength and the SAW at 391 MHz center frequency has demonstrated a time-bandwidth product of 4.2×10^5 . We plan to continue this research through other support by completing the hybrid integration and carrying out detailed theoretical analysis to determine the ultimate performance figures of the integrated correlator module.

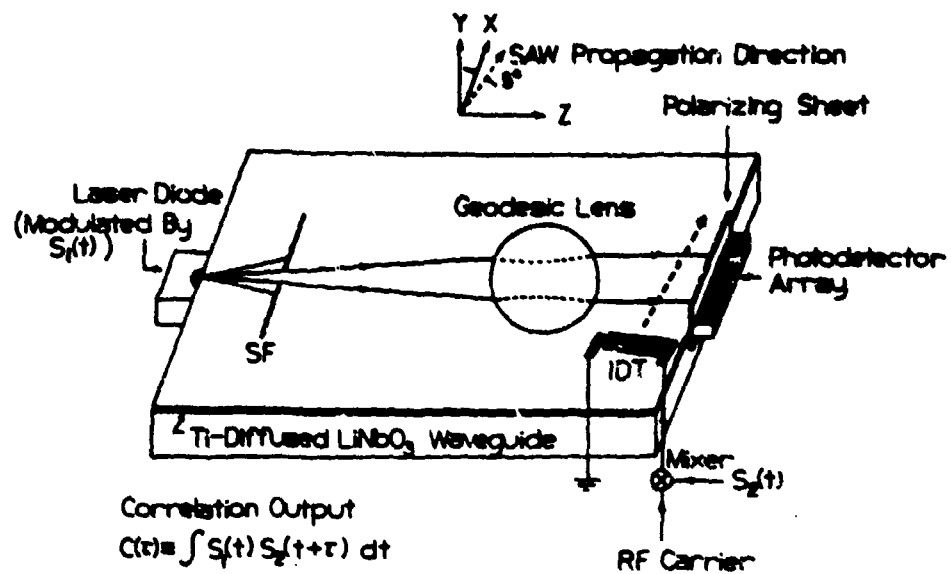


Fig. 7 Acoustooptic Time-Integrating Correlator Using Anisotropic Bragg Diffraction And Hybrid Optical Waveguide Structure



Fig. 8a

- (A) Waveform Of A Pulse-Modulated Input Signal
(Time Scale: 0.05 μ s per major division)
(B) Autocorrelation Waveform Of The Modulating Pulse
(Time Scale: 0.1 μ s per major division)

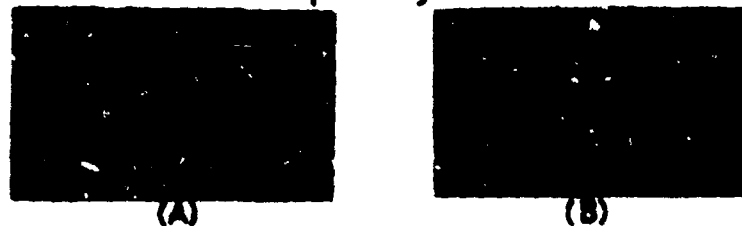


Fig. 8b

- (A) Waveform Of A Square Wave-Modulated Signal
(Time Scale: 0.05 μ s per major division)
(B) Autocorrelation Waveform Of The Modulating Square Wave Signal (Time Scale: 0.1 μ s per major division)

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IV. LIST OF PUBLICATIONS

1. K.Y. Liao, C.C. Lee, and C.S. Tsai, "Time-Integrating Correlator Using Guided-Wave Anisotropic Acoustooptic Bragg Diffraction and Hybrid Integration," Sixth Topical Meeting on Integrated and Guided-Wave Optics, Jan. 6-8, 1982. Technical Digest, pp. WA4-1 to -4, IEEE Cat. No. 82CH171904.
2. C.S. Tsai, C.C. Lee, and K.Y. Liao, "RF Correlation With Integrated Acoustooptic Modules," 1982 Wescon Convention Records, Session 26, Real-Time Signal Processing Using Integrated Optics Technology, pp. 26-3-1 to 26-3-4.
3. C.C. Lee, K.Y. Liao, and C.S. Tsai, "Acoustooptic Time-Integrating Correlator Using Hybrid Integrated Optics," 1982 IEEE Ultrasonics Symp. Proc., pp. 405-407, IEEE Cat. No. 82CH1823-4.
4. O. Yamazaki, C.S. Tsai, M. Umeda, et al, "Guided-Wave Acoustooptic Interaction in GaAs-ZnO Composite Structure," Proceedings of 1982 Ultrasonics Symposium, pp. 418-421, IEEE Cat. No. 82CH1823-4.
5. C.J. Lii, C.C. Lee, O. Yamazaki, L.S. Yap, K. Wasa, J. Merz, and C.S. Tsai, "Efficient Wideband Acoustooptic Bragg Diffraction in GaAs-GaAlAs Waveguide Structure," (To Appear in the Proceedings of 1983 International Conference On Integrated Optics And Optical Fiber Communications, June 27-30, Tokyo, Japan).
6. C.S. Tsai, "Hybrid Integrated Optic Modules for Real-Time Signal Processing," Invited Paper, presented at 10th International Optical Computing Conference, April 6-8, 1983, MIT, MA. (To be published).
7. K.Y. Liao, C.S. Tsai and J.K. Wang, "Acoustic Phase Distortions from Tilted Finger Chirp Transducer and Their Effects on Acoustooptic Bragg Diffraction," (to be submitted to IEEE J. Quantum Electronics).

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VI. ADVANCED DEGREES AWARDED

Ph.D. Thesis

K.Y. Liao, Thesis Title: Wide-Band Real-Time Signal Processing
Using Integrated Optics (April 1983).

M.S. Thesis

M. Umeda, Thesis Title: Guided-Wave Acoustooptic Interactions
in GaAs Waveguide (September 1982).